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Intelligent viewing control for robotic and automation systems

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ABSTRACT

We present a new system for supervisory automated control of multiple remote cameras. Our primary purpose in developing this system has been to provide capability for knowledge-based, "hands-off" viewing during execution of teleoperation/telerobotic tasks. The reported technology has broader applicability 10 remote surveillance, telescience observation , automated manufacturing workcells, etc. We refer to this new Capability as "Intelligent Viewing Control (IVC)," distinguishing it from a simple programmed camera motion control. in the IVC system, camera viewing assignment, sequencing, positioning, panning, and parameter adjustment (zoom, focus, aperture, etc.) are invoked and interactively executed in real-time by a knowledge-based controller, drawing on *a priori known task* models and constraints, including operator preferences. This multi-camera control is integrated with a real-time, high-fidelity 3-D graphics simulation, which is correctly calibrated in perspective to the actual cameras anti their platform kinematics (translation/pan-tilt). Such merged graphics-with-video design allow's the system user to preview and modify the planned ("choreographed") viewing sequences. Further, during actual task execution, tile system operator has available both the resulting optimized video sequence, as well as supplementary graphics views from arbitrary perspectives. IVC, including operator-interactive designation of robot task actions, is presented to the user as a well-integrated video-graphic single screen user interface allowing easy access to all relevant telerobot communication/command/control resources. We describe and show pictorial results of a preliminary IVC system implementation for telerobotic servicing of a satellite.

keywords: robotic sensing, automated manufacturing workcells, viewing systems, remote viewing, teleoperation, video surveillance, AI planning, 3-D graphics simulation, operator displays, graphics user interfaces

1. INTRODUCTION AND BACKGROUND

The design of effective viewing systems for remote robotic tasks, that is, "telerobotic [1, 2]" operations, is critically important. Several decades of practical experience with teleoperation (manual remote control of robots) in nuclear, undersea and more recently space applications [3, 4] show that as much as 6[]) percent of operator task execution time may be devoted to viewing versus manipulation [5] -- indeed, just the basic physical design and perceptual optimization of related l~~orl(~clll:lr/stereo/l~~tJltical~~cr:t systems has been a research discipline in itself [5, 6, and refs. thq-tin]. More generally, and at higher levels of abstraction, the cognitive workload of managing and integrating remote viewing resources -- the positioning, sequencing, panning, zooming, and focussing of several cameras -- is sufficiently high that a second system operator is often assigned solely to this function. Even when given this assistance, the robot operator maintains a complex dialogue of camera coordination (secondary task load) that distracts from the primary manipulation objective. 'J'bus, developments which coherently organize and automate viewing procedures are significant toward improved tasking efficiency. Similarly, developments which improve 3-D task comprehension under adverse viewing conditions (limited or obstructed views, limited acuity, etc.) arc significant toward improved tasking flexibility. In this paper, wc describe. the preliminary development and demonstration of a new viewing system which makes contributions to both these design objectives. We describe an knowledge-based control and communications architecture that provides a telerobot operator with an automated viewing sequence appropriately "choreographed" (perceptually structured and temporally synchronized) with his real-time robot motion commands. This high-level viewing control architecture. is integrated with a high-fidelity rmi-time 3-D task modeling & graphics display environment, which itself is visually calibrated in geometric perspective with, and overlaid on direct multi-camera viewing [7]. The graphics facility can be used in both oft-line task planning-preview, and also on-line task visualization-prediction. The operator thus has the added benefit, beyond the usual one of graphics-based robot task simulation, of being able to synthesize task percepts for arbitrary viewing constraints, e.g, "see" into an unobservable region when camera viewing information alone is insufficient, or develop a new "point-of-view" -- all geometrically registered with the real environment.

2. SYSTEM DESIGN

We are currently developing Intelligent Viewing Control (IVC) for telerobotic applications. In particular, we are exploring various ways in which telerobotic systems can be generalized not only for more efficient operations, but also for more flexible, robust control in the presence of uncertainties due to communications time delay, partial-and-obstructed viewing, and positioning and force variabilities of manipulator control. The general theme in our related lab work is the design, demonstration, and evaluation of intelligent automation interfaces fostering cooperative, higher-level man-machine control. One design and implementation aspect of this work is IVC; another aspect is a complimentary development of "Intelligent Motion Control [8]," as later briefly noted. In general, we are developing and integrating these new capabilities in the framework of a functionally *distributed space telerobotics* (DST) operations, where "distributed" connotes a system in which:

- the operator and robot are physically separated, the robot often in a hazardous, geometrically constrained environment
- control functions are shared between operator manual skills and robot site automatic sensing & controls
- multiple robot cameras-sensors exist, only some of which (if any) may be useful at a given point in a task sequence
- time delays, often unpredictable, separate the operator and robot perceptions & actions.

2.1 A DST functional architecture

In Section 3, we will describe the physical architecture of our lab, and the current hardware/software implementation of IVC within same. Here, we first outline the underlying functional design of IVC.

As shown in **Figure** 1, the overall DST operational architecture consists of several devices each connected to a central control hub. Knowledge is distributed among the various devices comprising the system. The central control hub provides access to these system devices and top-level access to all distributed knowledge objects. The user interface provides for low-level commanding of all system devices, action-level commanding of individual mechanisms, and semantic-level commanding of coordinated actions involving multiple mechanisms or multiple task steps. The user is also provided with controls which affect the extent to which actions of mechanisms (including graphics) are linked, and affect the amount of opt'rater participation required during the course of performing a task. Independent computational processes within the central control hub support operator command interaction, send commands to the system devices, and handle synchronous feedback from system devices. The following is a brief outline of what capabilities are implemented in the architecture:

- System Devices: The four main system devices in the current IVC implementation are: 1) a robot controller, 2) a camera controller, 3) a video switcher, and 4) a graphics engine with geometric database. All interfaces with these system devices are in ASCII text, making it possible for the user to intervene at the lowest device level at any time if necessary. histories of device interactions are maintained.

- System Knowledge: Task-space knowledge is object-oriented, with objects distributed as appropriate among the system devices. Geometric knowledge is contained within the graphics database. Knowledge of mechanism kinematics resides both in the graphics system and in the appropriate controller. Coordination and conversion knowledge resides within the central control hub.

- Control Actions: Actions cause motion in the task space (or simulations in the graphics space). Simple actions involve single objects within the distributed knowledge base. Multi-object and multi-manipulator semantically primitive actions are built upon simple actions. These semantic actions, together with tasks, involving sequences of actions, are contained wholly within the central task control hub. Controls, set by the. operator, affect the behavior of semantic actions and tasks. These controls turn on-and-off the linking between mechanisms associated wit bin semantic actions and specify availability of, or constraints on the utilization of, mechanisms for automated intelligent operator assistance.

- Operator Interface: The operator interface, as illustrated in **Figure** 2, provides the user with menu and interactive command line access to each of the devices, actions, semantic actions, and treks that are defined in the system. Graphics images show available camera views at the remote site. Live video of the currently selected camera view is captured and selectively displayed.

2.2 IVC knowledge components

Intelligent Viewing Control is based upon a semantic linking between manipulations being performed and constraints on viewing the action. For example, in a related development by Wakita et al. of MITI-Electrotechnical Laboratory on "automatic camera work" for pick-and-place operations [9], cameras pan and tilt to continuously view a fixed point between the fingers of the gripper. Cameras zoom-in during moves to close proximity of contact (move_to_grip) and moves making contact (grip and put_it_on); cameras zoom-out during moves leaving close proximity (depart) or during long free-space motions (move_to_approach for place). Semantic linkage is embodied within object methods implementing pick-and-place. By contrast, in Intelligent Viewing Control, the semantic linkage between manipulation actions and corresponding camera actions are implemented within *two separate parts of the DST architecture*. This architectural (and syntactic) decoupling of actions enables the generalization of camera control from "scripted object-manipulator viewing behaviors," to far more general cases where camera actions at a given point in the task sequence can be made context-dependent [10, and refs. therein] on prior, current, and posterior task knowledge, including the task interaction constraints (static and dynamic geometric contact, viewing obscuration, etc.).

Task dependent "fixtures [11]," viz. sets of one or more reference frames associated with an object to be acted upon, are implemented within the geometric database portion of the object. These fixtures provide the knowledge needed by the intelligent behaviors within the remote robot controller. They provide information about the location and spatial scope of the behavior, thereby specifying constraints on the focus of attention appropriate for viewing the behavior.

Semantic actions, which link objects with actions of mechanisms and link actions of multiple mechanisms, contain procedural information for intelligent viewing. Each semantic action is a multi-step procedure involving graphical, camera, and robotic devices:

- choose focus of attention
- simulate action in graphics
- command camera motion
- command robot motion
- update graphics per robot motion feedback

Camera motion may either be completed before, or be concurrent with robot motion. The focus of attention may be the robot manipulator, a tool, or an object being worked on. Steps within the sequence may be enabled or inhibited via controls set by the user.

3. SYSTEM IMPLEMENTATION

The JPL *Telerobotic Operations and Intelligent Controls (TROPICS)* Laboratory, **Figure 3**, is designed and configured to perform research & development in teleoperation and telerobotics relevant to space applications, among others. TROPICS Lab provides an end-to-end system for telemanipulation, including a variety of operator interfaces at the local site, a dual arm manipulation system with 5 different cameras at the remote site, and the required communication and control connectivity to exercise the system in various operational modes, from conventional teleoperation to time delay semi-autonomous telerobotics. We show the TROPICS Lab block implementation architecture in **Figure** 4. The following paragraphs describe the TROPICS facilities and their organization in more detail, and outline the IVC software implementation in this lab environment; see also [12, 13], regarding controls.

3.1 TROPICS Lab local and remote sites

<u>Local Site (Operator)</u>: At local site, the operator is offered 3 color video monitors and 2 workstations (by Silicon Graphics and Sun Microsystems) for viewing. The graphics workstation is equipped with Videolab in or'tier' to display live video on its monitor. The Sun Sparc10 contains an XVideo™ board by Parallax and provides the ability to display live video on the Sun monitor and more importantly to perform hardware-based JPEG compression of images. Video signals are routed to the monitors and workstations through a computer-controlled 8x8 video switch. In addition to the conventional computer interfaces (GUIs, mouse, voice, etc.), the operator has at his disposal a SpaceBall and dual 6 degree-of-freedom (dof) Force Reflecting Hand Controllers. The FRHC's are controlled at the high level by a single VME system (running the VxWorks Real-time OS) which is memory-mapped to the servo level Universal Motor Controllers (UMC).

Remote Site (Robot): The remote site consists of two comprehensive manipulation and viewing systems. Dual redundant 8-dof AAI robots are each equipped with a force sensing, parallel jaw instrumented "Smarthand" (JPL design with integrated force-torque F/T sensor, on-board signal pre-processing, etc.). A VME system (running VxWorks) controls these robots in task space and is memory mapped to the joint-level servo controllers (UMC's). The remote VME system also controls the viewing system, which consists of three gantries (4-dof each) used to position cameras and four cameras (including a stereo pair) with computer controllable focus, iris, and zoom. A fifth camera is optionally mounted on one Smarthand for "eye-in-hand" viewing.

Intersite Communications: Ethernet-based communication is used between the local and remote site for telerobotic experiments, and this interface has been used to connect these facilities to other systems outside of JPL for simulated time-delay space operations, including NASA's Goddard Space Flight Center [14], the Electrotechnical Laboratory of MITI in Tsukuba, Japan [8], and the GRASP Lab of the University of Pennsylvania [15]. This Ethernet communication can be supplemented with other JPL-NASA resources for video/data transfers, e.g. in some the preceding operations we have utilized the NASA-Select Channel satellite communication link, and ISDN/ATM options also exist.

3.2 IVC software implementation

The DST central control hub (cf. Figure 1) is implemented in Allegro CommonLisp with the CommonLisp Interface Manager, Version 2 (CLIM-2). The commercial Deneb Robotics, inc. TELEGRIP™ package is used for the graphics simulation and geometric database support. The video switch interface, camera controller, and robot controlled are all implemented in custom C software. We note in passing that the robot controller architecture has recently been augmented for behavior-based, teleprogrammed operations (this work has been done in collaboration with colleagues at The University of Pennsylvania [15]). Using this element of *Intelligent Motion Control* [8], we have shown the robot can respond instantaneously with automatic, qualitative changes of force-and-position control strategy, as based on current operator input, *a priori* task model information, and real-time sensor feedback,

The central hub is connected to the four system devices via sockets, with ASCII text interfaces to each. The TELEGRIP™ interface utilizes the J>rc-defined CLI command language and protocol: each command to TELEGRIP™ is followed by a single response, The video switcher interface also has an alternating command/response protocol. The camera controller interface is currently driven open loop, with commands to the controller, but no responses. The robot controller interface is asynchronous: Commands are sent in groups, with execution of motion commands starting upon the receipt of a numbered "EndGroup" command. During robot motion, a stream of position and force feedback data are returned. An independent process within the central hub continuously monitors robot controller feedback, maintains the latest robot force. and position states and monitors for command group completion status. This process also updates the graphics display, if TELEGRIP™ is connected and graphics update upon feedback control is enabled.

Existing TELEGRIP™ models for most of the TROPICS Laboratory remote site objects and mechanisms were used, but new models for the. 2-DOF translational camera positioning mechanisms were created. The pan/tilt heads were not modelled: the camera is modelled as a point at the intersection of the pan and tilt actuator axes. Manipulation fixtures are modelled as tags attached to paths, which in turn are attached to parts and devices in the TELEGRIP™ terminology.

The supporting central hub software consists of: 1) the CLIM menu interface, 2) connections to system devices, 3) extensions to the robot task object models, 4) semantic action functions, and 5) system control parameters. The CLIM interface. provides mouse and keyboard command access to CLIM command functions. These functions can be called by any CommonLisp functions, including other CLIM commands. This permits the layering of multiple levels of access and intelligence within the. same interface. Device models consist of the active socket object plus device-specific control parameters, One such parameter enables or inhibits the. automatic updating of graphics from robot controller feedback data. Device models also maintain command and response histories.

"Simple actions" are functions which generate appropriate text string commands to be sent across the socket interface to the device. "Semantic actions" are functions which assemble the appropriate data and call the appropriate set of simple actions, Semantic action functions follow the. CLIM command function structure, making them available to the operator through the menu and command interface. Semantic actions communicate all information needed by the device to perform its portion of the task. For example, camera and robot move commands within the TELEGRIP™ CLI language reference a previously selected "current" camera and "current" robot which are internal TELEGRIP™ state information. Relevant internal states are actively set by each semantic command to ensure. its executional integrity. This conservative, semantically complete approach to communications is necessary to implementation of a system which allows operator intervention at multiple levels of abstraction.

The cameras are the only objects which have a significant portion of their data maintained within the DST central hub. The models contain the current camera translational positions and the pan and tilt angles. The camera objects also compute the pan and tilt angles required for viewing an object of interest. Other information such as translational range of motion and the name of the camera in each of the TELEGRIP™ and camera controller interfaces is also maintained.

All communication of position information throughout the system is in millimeters x, y, and z relative to a global world frame. Communication of orientation information is in degrees of roll, pitch, and yaw with respect to TELEGRIP™ and in radians with respect to the robot controller. Camera control commands are given in millimeters of translation in device prismatic joint space, and in radians of pan and tilt.

3.3 Calibration of 3-D graphics views to actual camera viewing

We have recently developed graphics interfaces [7, and refs. therein] which are rigorously calibrated in viewing perspective and scale to the remote task. The essence of these developments is a 3-D real-time graphics interface in which high-fidelity real-time renderings in either wire-frame or solid modeled (shaded polygonal) surfaces can be shown in a transparent graphics-on-video overlay mode, and in which salient geometric features of both the robot and workspace objects are modelled. The graphics can be rendered at flicker-free NTSC monocular display rates, in full geometric calibration to both the actual multi-camera views and object positions-and-poses. Thus, once such a virtual environment calibration is established, it is possible, within limits of modeling fidelity, to *synthesize realistic task view presentations from an arbitrary viewpoint, upon which an operator can confidently base his predictive manual control (or that of an automated control procedure)* -- this is a very important facility to have when performing robotic operations in obstructive, limited access areas -- e.g., for inspection, servicing, and salvaging operations in-and-about complex platform structures.

Such 3-D calibration, which is canonical to machine vision and photogrammetry, computes camera viewing parameters given a known correspondence between 3-D object points and their modelled-and actual image plane projections. In robotics, this computation is most typically performed as a matrix estimate of the extrinsic viewing parameters, given a known camera. in particular, for our application, the graphics viewpoint and projective transformation must be made to match that of the. camera. In our approach, which is performed interactively and uses the robot itself as a calibration fixture, the operator:

- selects an overconstraining set of 3-D points on the robot geometric model
- identifies the corresponding point locations in the camera(s) image
- seeks the "best-fit" estimate of a viewing transformation which would produce the same projective point mapping for the graphics (including viewport parameters of scale, aspect, cropping, etc.).

In actual practice, we select object interest points using the "pick" function call of a Silicon Graphics standard GL graphics library, which automatically returns the 3-D geometric model coordinates of operator-designated 2-D screen coordinates, We have used several different optimization algorithms to estimate the 4x3 calibration matrix for an idealized "pinhole" camera linear perspective model. These static task estimation approaches include linear and non-linear least squares (NLS), with NLS allowing orthonormalization of the rotation matrix, while retaining a least squares fit; for NLS implementation, the rotation is alternatively represented by a pan-tilt-swing decomposition,

Once a correct calibration is established, the graphics and camera images then provide. a fully registered 3-D viewing perspective of robot. We subsequently apply a similar procedure to estimate the Cartesian location and pose for modeled objects of interest in the remote workspace. In addition to "localizing" real objects with respect to the geometrically calibrated robot workspace, the operator can also assign virtual location indicators (so-called "tag-points"). These overlaid graphic markers, seen by the operator as positioned-and-oriented arrows or local coordinate frames, are useful references for intermediate staging and verification of robot trajectories and can in fact be used to set up target endpoints between which the operator can command an autonomously controlled straight line trajectory when deemed safe.

Figure 5 illustrates the above concepts, and shows their application to an actual time-delay telerobotic servicing operation [14]. At present we assume *a priori* known object geometries; we have begun to explore approaches to incremental interactive object modeling (e.g., as will be important in handling less-structured contingency tasks with unexpected events).

4. PRELIMINARY EXPERIMENTS AND FUTURE DEVELOPMENT

4.1 Proof of Concept

To date, we have performed some simple task sequences to verify the IMC interface operations, and its communication/command/control integration with the "remote site" of the TROPICS Lab. The work we have done is based on a ground lab simulation of space servicing, modeled after NASA's Solar Maximum EVA Satellite Repair (SMSR) Mission. This mission, performed on shuttle flight STS-13 in 1984, recovered, repaired, and redeployed a space observational instrument which required changeout of a failed AAS (attitude-articulation system) and upgrade of a MEB module (main electronics box). The EVA repair work was performed by two fully suited astronauts working in-and-from the shuttle payload bay over a physically and mentally taxing period of several hours; the task required mission pre-operational training and preparations of almost a year. The SMSR task sequence is rich in requirements and technical challenges for robotic implementation, as we have reported in earlier work [16]: thermal blanket removal, hinge attachment for electrical panel support, opening of the panel, removal of electrical connectors, re-aligning of cable bundles, panel replacement, securing of parts and cables, re-plugging of electrical connectors, closing the panel, and thermal blanket reinstatement. We have developed within our lab a realistic replica of the SMS service bay, including a flight replica equivalent of the MEB panel access, wherein an operator must cut Kapton tape, remove thermal foil, open the panel access door, etc., to initiate the actual repair/upgrade procedures. As regards preliminary testing of the IVC interface, we have performed various operator-interactive proximity robot operations about the SMS panel access door, servicing tool caddy, and other spacecraft features, verifying such functions as automated view tracking of robot effector, focus-to-grip, task-object-focus, etc. These operations verified proper knowledge-base driven allocation of the camera views, real-time coordination of viewing with high-fidelity 3-D solid shaded task simulation for all modeled cameras (rear, side, overhead), simple task focus-of-attention, easy access to all relevant system command/control functions, and a well-integrated video-graphics presentation. The general command-and-control procedures of related task manipulation, as depicted in the IVC operator interface display of **Figure 6**, are currently semi-autonomous -- the operator designates appropriate start-finish target frames and primitives that can be executed under simply trajectory control and or guarded contact compliance. More generally, we will extend these procedures to casually structured high dexterity time-delay teleoperation [12] or teleprogramming [8, 11, and 15]. Integration of the IVC interface with such computer- assisted manual controls is yet to be done, and offers extremely rich possibilities for flexible, efficient remote robotic operations.

4.2 Summary and Future Directions

We have designed, developed and demonstrated an architecture for Intelligent Viewing Control (IVC), with emphasis on reducing operator workload in telerobotic manipulation; the IVC design should have broader applicability to remote surveillance, telescience observation, automated manufacturing workcells, etc. Some key points of this development, and status to date are:

- full access to all dc.vices and all high and low-level system functions is provided within the IVC operator interface, thereby enabling smooth and continuous human intervention as desired or necessary
- intelligent assistance can be enabled, disabled, or restricted to assign specific devices to direct operator control, and this capability also supports comparative performance analysis
- multi-action viewing tasks have not yet been implemented, wherein it is desirable to contextually link viewing constraints from consecutive steps to reduce the number of perceptually disorienting changes in camera selection and motion
- fixture models, as used in the above-noted beh:lvio;-based robot control, have proven useful for determining where to place primary attention cm robot positioning -- future enhanced fixture models should include viewing-specific information, such as constraints on associated viewing direction as arise from geometric obstruction, orthogonalized viewing presentation, etc.
- experiments with IVC to date to date have involved only free.-spacc and proximity motions, and a next design objective is to consider space-operations-related contact tasks (including integration of IVC with the complementary Intelligent Motion Control concept for locally situated behaviors).

5. ACKNOWLEDGEMENTS

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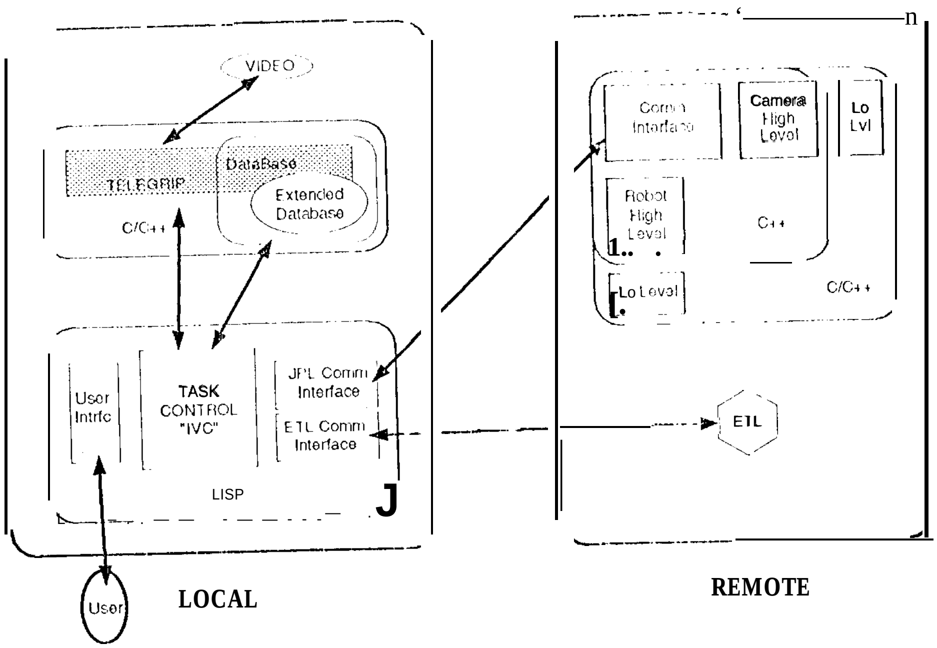
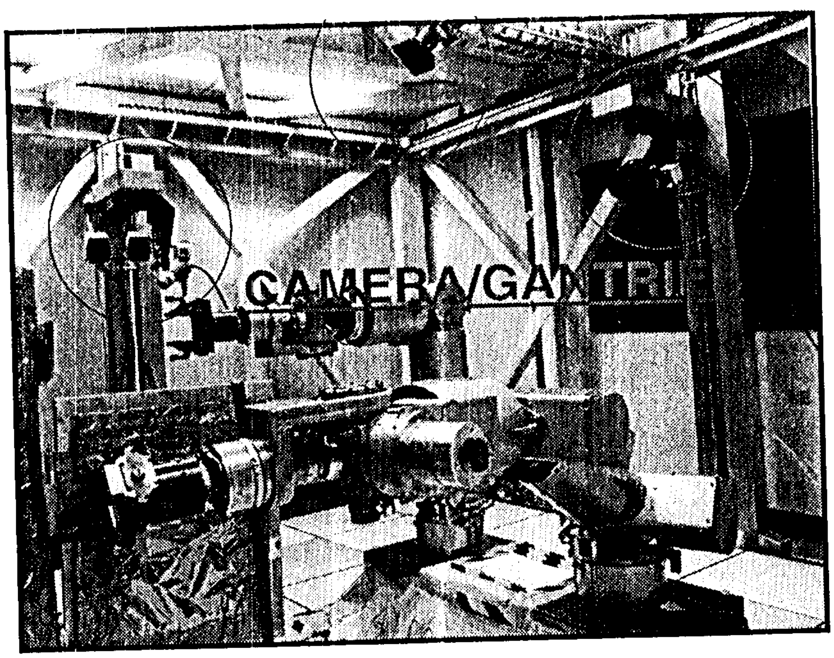
DST Architecture for Intelligent Viewing Control





TROPICS Remote site

Figure 1. *Operations Architecture for Distributed Space Telerobotics*: (top) A user interface and task control hub at the local site command and coordinate knowledge among local and remote devices in the distributed system (ETL refers to communication link with MITI-Electrotechnical Laboratory as part of an ongoing NASA-MITI collaboration. (bottom) JPL TROPICS Lab computer-controllable camera gantries (overhead, side, and back wall)

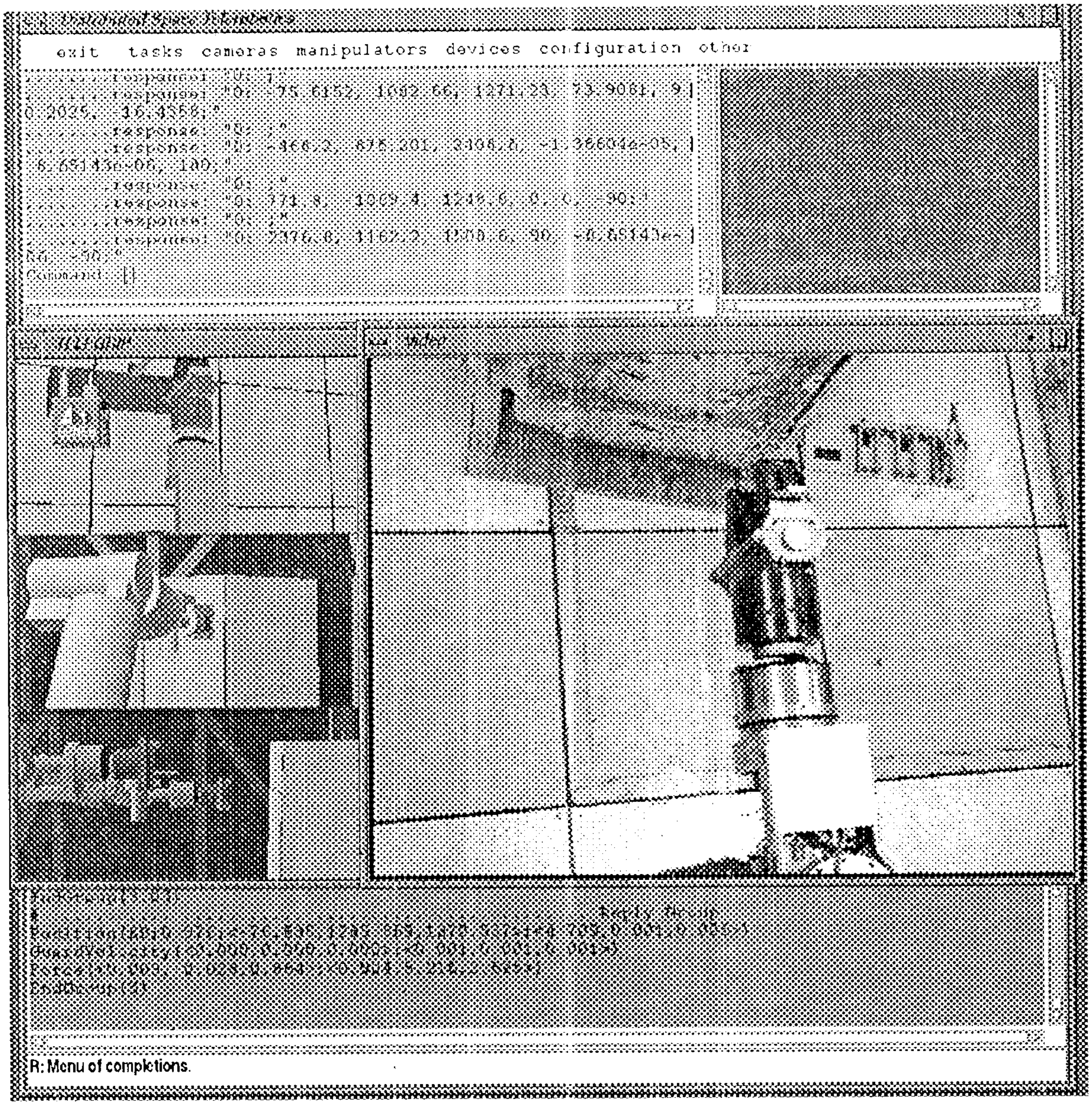


Figure 2. ***User Interface for Intelligent Viewing Control***: the screen includes menu and command interfaces which provide access to all system capabilities, ranging from high-level task directives to low-level device commands. Synthesized graphics images correspond to available remote camera views. Live video of the preferred view is captured and presented to the operator.

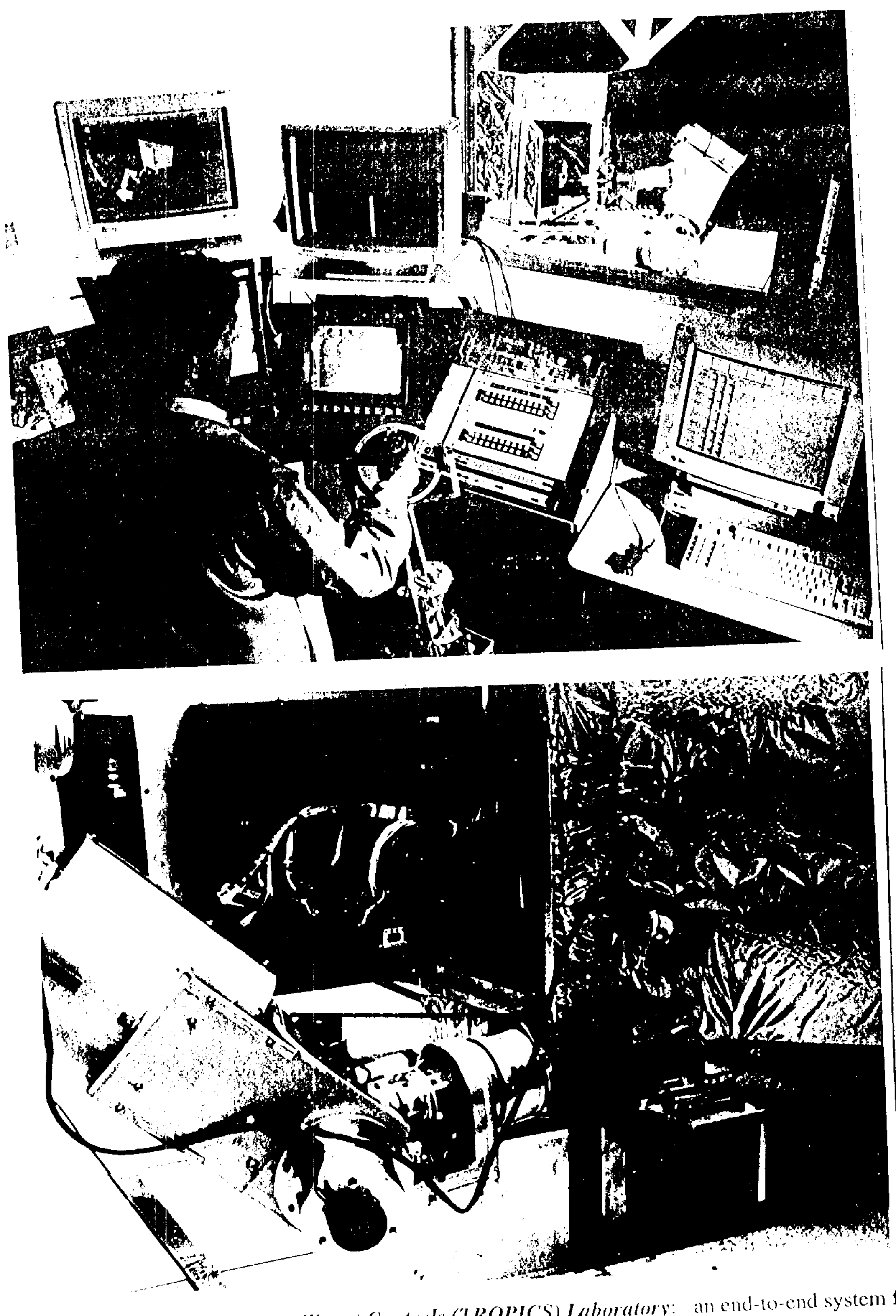


Figure 3. *JPL Telerobotic Operations and Intelligent Controls (TROPICS) Laboratory*: an end-to-end system for telemanipulation, including a variety of operator interfaces at the local site, a dual arm manipulation system with 5 different cameras at the remote site, and the required connectivity to exercise the system in various operational modes, from pure teleoperation to time delay semi-autonomous telerobotic control. Shown here performing one step of simulated Solar Maximum Satellite repair (in such conventional practice, without benefit of the Intelligent Viewing Control system, a second operator is dedicated solely to manual control of the three cameras in the remote site workcell).

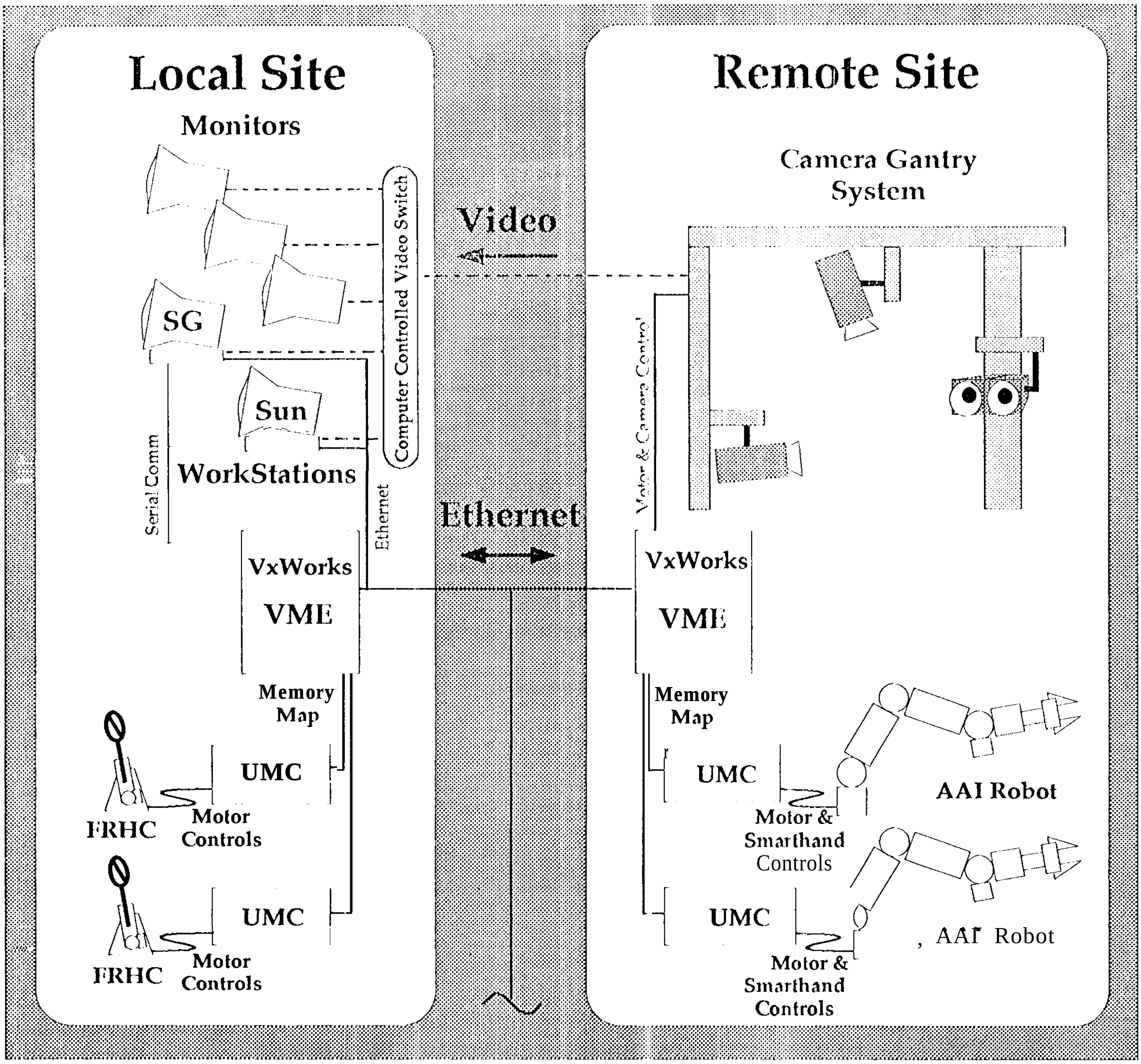


Figure 4. *JPL Telerobotic Operations and Intelligent Controls (TROPICS) Laboratory Implementation* **Architecture**

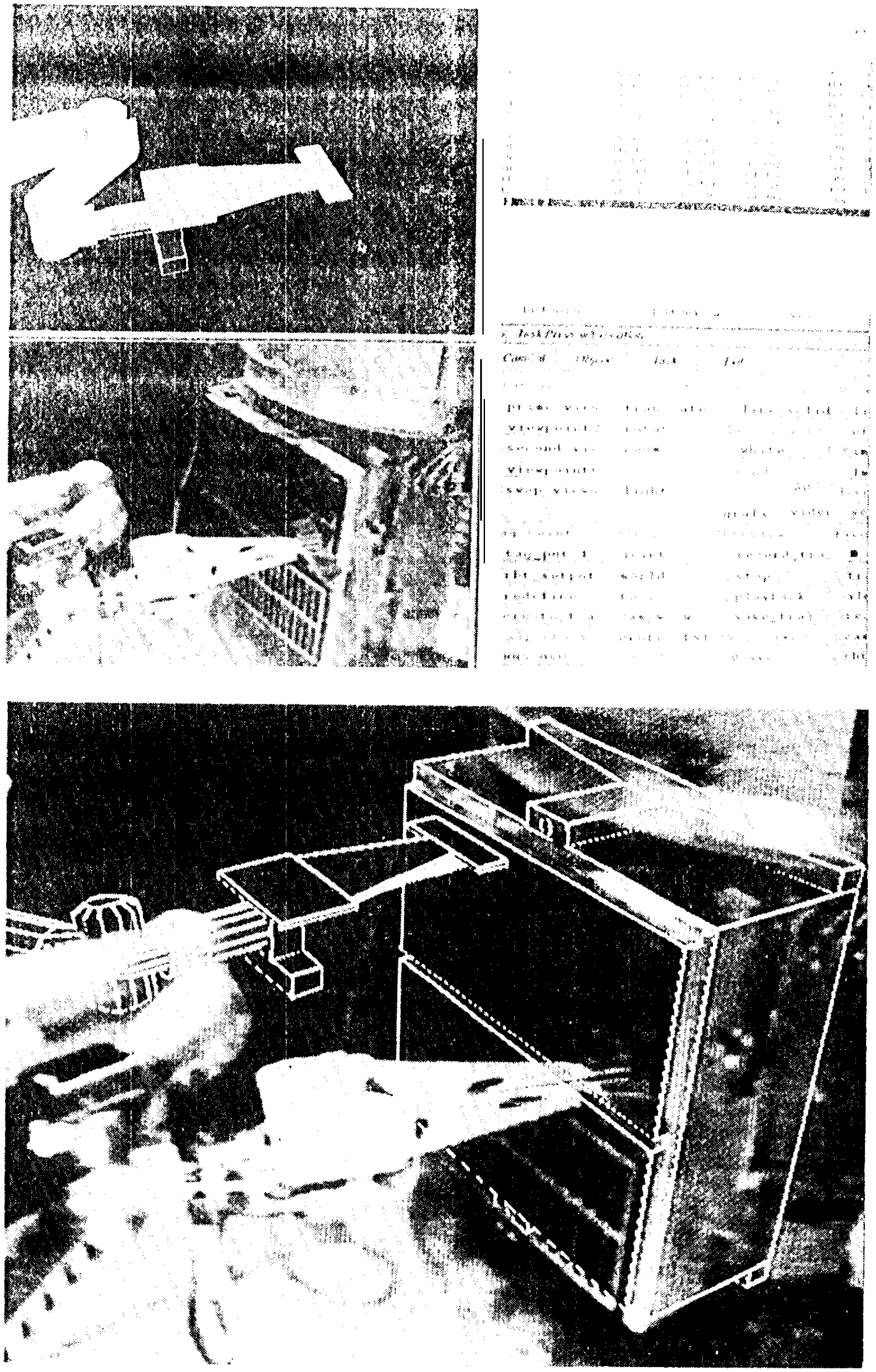


Figure 5. ***3-D Calibrated Graphics and Real-Time Video Overlay***: (top) selecting points for use in computer-based 3-D matching of graphics viewing perspective to the remote site camera views: (bottom) having established the calibration, the operator uses graphics-on-video overlay for predictive control of the robot under teleoperation time delay.

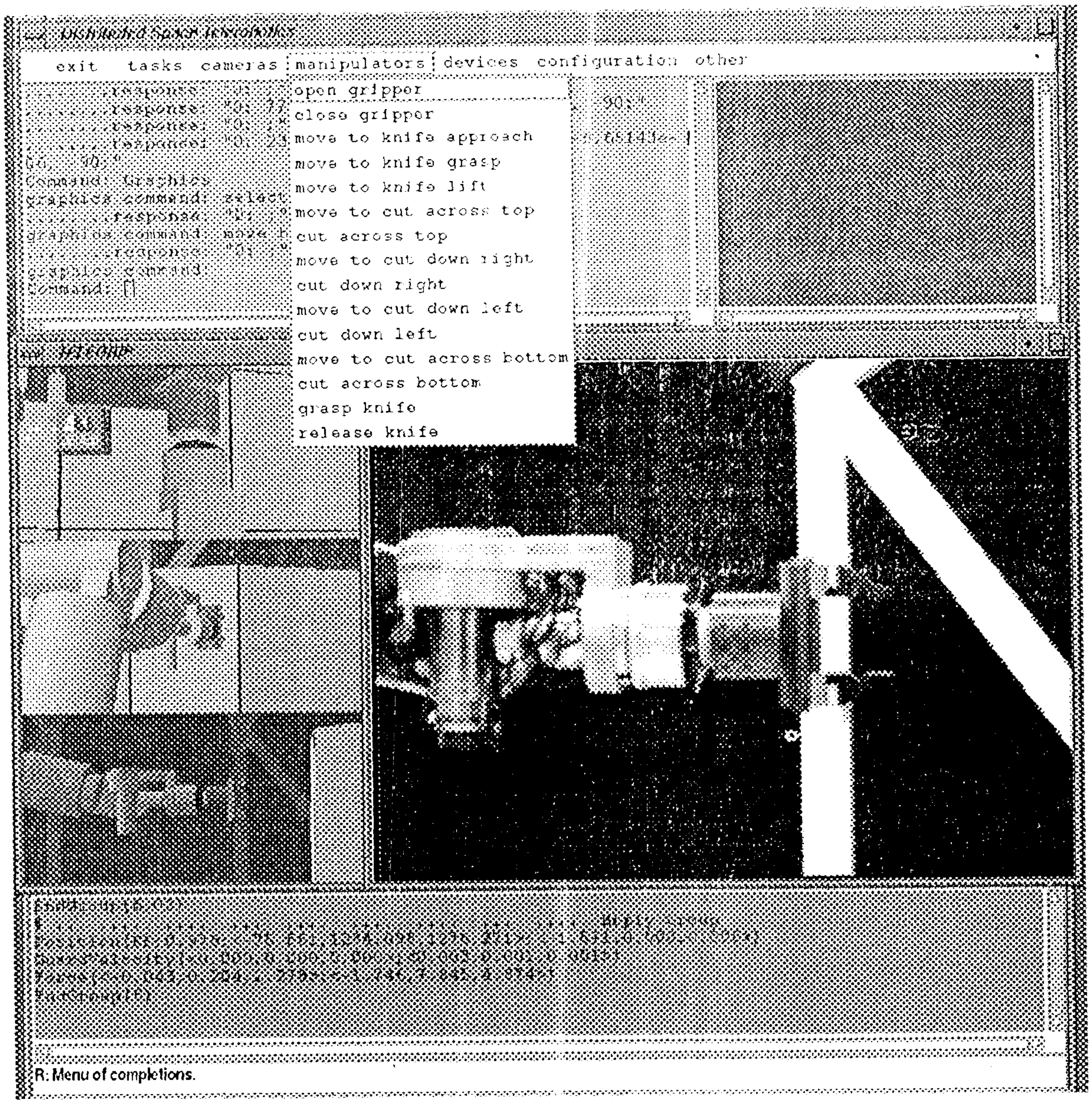


Figure 6. ***Intelligent Viewing Control (IVC):*** IVC enables knowledge-based planning of the camera views, high-fidelity 3-D solid shaded view synthesis for all modeled cameras (rear, side, overhead), task focus-of-attention and integrated presentation of a video-graphic view most appropriate to, and time-synchronized with, each step of a task. In our IVC experiments to date (*example shown here: simulated proximity operations to satellite*), manipulation has been semi-autonomous, and well-structured -- the operator designates appropriate start-finish target frames and primitives which are executed under simply trajectory control and/or guarded contact compliance.